A.R.Horrocks, Burning Hazards of Textiles and Terminology, in: *Update on Flame Retardant Textiles: State of the Art, Environmental Issues and Innovative Solutions*, J. Alongi, A.R Horrocks, F. Carosio and G. Malucelli (Eds), pp.1-20, Smithers Rapra, Shawbury, UK (2013)

Chapter 1

Burning Hazards of Textiles and Terminology

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1.1 Introduction

The particular hazard posed by burning textiles, especially those based on the natural cellulosic fibres cotton and flax (as linen), was recognised during early civilisations and the use of salts like alum has been used since these times to reduce their ignitability and so confer flame retardancy. These risks remain with us to this day as a consequence of the intimate character of most textiles, primarily as clothing, and in the immediate domestic environment, coupled with the high specific surface area of the fibre-forming polymers present, which enable maximum access to atmospheric oxygen.

Thus the need for flame retardant textiles has been recognised for many years and the significant patent of Wyld [1] in 1735 which described a finishing treatment for cellulosic textiles using alum, ferrous sulphate and borax and Gay-Lussac's first systematic study of the use of flame retardants in 1821 [2] have formed the basis for the more recent and modern approaches to developing heat and fire resistant textiles.

The most significant developments have occurred since World War II and especially with the need to confer durability to laundering as a significant feature in addition to the underlying flame retardant character. The period up to the late 1940s was significantly reviewed by Little [3] with an obvious focus on flame retardant cotton since the newer synthetic fibres were still under development.

During the 1950-80 there exists a significant literature which has been comprehensively reviewed during the mid-1980s [4, 5] and so individual references during this period will not otherwise be referred to unless essential to the arguments within this current chapter. It was in this post-war period that the need to reduce fire-related fatalities and injuries became of greater importance as greater consumer safety awareness increased and governments took notice of the human and financial costs of fire both in the domestic and work environments. Coupled with this was the greater personal wealth in the post-war society enabled far greater use of textiles in the home and public buildings with a consequential increase in their fuel loadings and their fire hazard. These factors were the drivers for developing flame retardant textiles for use in the domestic, public and work environments.

Since then there has been a number of comprehensive reviews that have critically reviewed research both during this period and since then and which has led to the current armoury of commercial flame retardants available [6-8].

Even more recently Horrocks has presented a historical perspective in attempts to reflect the challenges posed by today's socio-economic environment with the underlying research challenges addressed during the last 70 years [9].

Analysis of the above reviews suggest that up to about the 1970-80 period, the established durable and flame retardant treatments for cotton and wool fibres as well as those additives and comonomers introduced into both regenerated (e.g. viscose) and synthetic (notably polyester, polypropylene and the modacrylics) fibres during manufacture were synthesised and developed into commercially–acceptable products. In fact it is probably true to say that the majority of currently available flame retardants for textiles and fibres reviewed very recently by Weil and Levchik [8] derive from chemical developments prior to 1980. These what my now be termed traditional flame retardant textile technologies are fully discussed in **Chapter 4**.

1.2 Hazards of burning textiles

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The need for fire retardant textiles is directly related to the hazard posed by textiles and regulations imposed by governments in the main and so it might be said that the whole field is regulation driven. Legislation and regulations are not only complex within a given country but often differ significantly between countries even when similar textile fire hazards are being assessed. These will be considered generally in **Chapter 2** as they relate to those textiles which are deemed to be particularly hazardous and so require levels of flame retardancy and fire resistance which deliver defined and acceptable levels of human and property safety in a developed world. However, before regulations can be drafted, there is the need for reliable and comprehensive fire statistics relating to the cost of fire in human life and property terms.

Across the world very few comprehensive fire statistics exist, especially those which attempt to relate deaths and injuries to cause, such as ignition and burning propagation properties of textile materials. World Fire Statistics, for example, concentrate on the loss of life and financial losses caused by fire and rarely consider the major causes at the material level [10]. However, national statistics do exist for many nations although their mode of collection and detail of substance differs from nation to nation and larger politico/economic groups like the EU do not collate them. However, it is by analysis of these statistics that nations and international groups can then demand and frame legislation and/or regulations for those textiles seen to be the most hazardous and which pose the greatest risk to life. An outline of those areas posing greatest risk and hence where legislation is more commonly adopted by a number of countries in Europe and the USA, is presented below.

The annual UK Fire Statistics [11] are some of the most comprehensive available and do attempt to provide information perhaps representative of a European country with a population of about 60 million. These are collected from the local and regional fire brigade records using a standard format and so relate only to fires to which the fire services have been called. There are other smaller fires, especially in the home, which may involve fire casualites to which the fire services have not been not called because the victims are taken directly to hospital and these are collected from UK hospital admission records by the Home Accident Surveillance Scheme (HASS), which until 2002 was administered by the former UK Department of Trade and Industry. Since then HASS has been accessible via the Royal Society of Prevention of Accidents web-site [12]. With regard to textile burning hazards, clothing fires and ensuing burn casualties are those which are most likely to involve attendance at a hosptital without involvement of the fire services. Recently Horrocks, Nazaré and Kandola analysed clothing burn incidence data using a number of sources [13], including HASS data for the period 1995-1998 [14] and from other sources on accidents involving burns and scald injuries over a period 1992-1996, which enabled 108 clothing fire accident data over the period 1990-2000 to be more effectively understood. Almost 50% of the clothing fire incidences involve nightdresses followed by dressing gowns and pyjamas. Frequency of accidents caused by ignition of nightdresses and dressing gowns taken together add up to a far greater total (70%) than pyjamas (20%). Moreover, 50% of fires involving pyjamas are considered to have been caused by the ignition of bedding. It has also been observed that burns involving the ignition of clothing (loose fitting garments in particular) usually prove to be more severe because of the intimate nature of such textiles. **Figure 1.1** presents the nightwear fatality data in graphical form. In clothing fires as in other UK domestic fires [11], the victims are predominantly the very young and the very old as shown in **Figure 1.2** for clothing fatalities during the period 1990 -1998 [13, 14].

Figure 1.1 and Figure 1.2

More generally and up to 2007, the UK statistics have demonstrated that while about 20% of fires in dwellings are caused by textiles being the first ignited material, over 50% of the fatalities are caused by these fires. **Figures 1.3** and **1.4** present typical data during the last 17 years during which period UK furnishing legislation [15] which prescribes minimum ignition criteria on both outer covers and fillings (including polyurethane foam) in terms of cigarette ignition and match ignition.

Figure 1.3 and Figure 1.4

The trends show that generally deaths from fires in UK dwellings have fallen from just above the 600 level in 1990 to about 350 or so by 2007 although during the period 1982 and 1988, the level fluctuated around 700 per annum. The trend in **Figure 1.3** for all textile materials shows an even more dramatic reduction from 346 in 1990 to less than half at 154 in 2007. This trend is reflected in that the parallel decreasing trends for furnishings and bedding (*see* **Figure 1.4**) caused by the need for defined levels of fire protection to both cigarette and match ignition of fillings and cover materials (and of mattresses and ticking in the case of bedding) as a consequence of the 1988 UK furnishing regulations [15]. Fatalities related to furnishings as the first ignited material in UK dwelling fires have decreased from 157 to 46 over the same period. After furnishings, bedding-related fires give rise to the next most hazardous textile in terms of fatalities and fire injuries and as the UK statistics for bedding show in **Figure 1.4**, the high levels of 130-140 annual fatalities occurring in the early 1980s have reduced to about the 40-50 level during the 2000-2007 periods. No comprehensive UK statistics were published for 2008 and 2009 but recently those for 2010/11 have appeared and these suggest that the above pattern has been maintained.

In terms of being able to quantify the impact of the current UK furnishing regulations [15] on these statistical reductions and while within the UK the mandatory installation of smoke alarms in new and refurbished UK dwellings has increased over the same period, Stevens et al have shown that about 140 lives are saved each year as a consequence of the introduction of ignition furnishing cover fabrics and fillings, primarily polyurethane foam [16, 17]. These researchers have estimated that over the period 1988-2002 lives saved for upholstery as the first item ignited in UK dwellings fires is 1,150 and injuries saved over the same period were 13,442 [17].

No other country publishes fire statistics as rigorously as the UK and these singularly fail to identify those fire hazards specifically related to the various textile materials apart from furnishing and bedding in the main. Kobes's analysis of European fire statistics [18] presented fire data for 18 of the EU nations in terms of fire and fire death incidence and could not find any data for Belgium, Cyprus, Italy, Luxembourg, Malta, Portugal, Romania or Spain. In terms of textile sources of fire ignition, the Netherland statistics for 2008 indicate that 29% of dwelling fire fatalities were caused by furnishings and 10% by bedding. These figures compare with the respective UK percentages of 13.9% and 13.3% for 2007.

In the US the National Fire Protection Agency (NFPA) state that over the 2006-2010 period, smokers materials (24%), candles (5%) and "playing with heat sources"(4%) accounts for about one third of all domestic fire deaths which currently have an total 2,590 deaths per annum [19]. Furthermore while only 7% of fires start in bedrooms, they cause 25% fire deaths and 20% injuries. Similarly, while the living areas are associated with only 4% fires, they are responsible for 24% fire deaths. It is obvious that many of these fires will involve a textile material although this is not directly stated. However, the US Fire Administration has published its research into bedding and mattress fires [20]. While over 10 years old, this research shows that of the total of about 20,800 fires occur due to mattresses and bedding and these caused about 2,200 injuries and 370 fatalities.

Children playing and smoking were responsible for 25% of these fires with cigarettes accounting for 26% and matches and lighters, 31%. Furthermore while 67% of injuries occurred to persons fighting to control the fires, 43% fatalities occurred while victims were sleeping. As a consequence, there are now US federal regulations relating to the flammability of mattresses and bedding as defined in CPSC 16 CFR Part 1632 for cigarette ignition resistance [21] and in CPSC published the regulation 16 CFR Part 1633 for an open flame source resistance [22] which latter came into effect 1st July 2007.

The impact of furnishings in the US is also significant and has prompted much debate over the last 10 years or so and while currently, there is no US federal flammability regulation for residential upholstered furniture, the Consumer Products Safety Commission (CPSC) has proposed a regulation (CPSC 16 CFR Part 1634) [23] that defines defined minimum smouldering and open flame ignition criteria for these products. This has prompted considerable development into blocking fabrics for furnishings and mattresses as recently reviewed by Nazaré and Davis [24].

In addition to the UK's strong position with regard to domestic furnishing regulations, most of the original 12 EU Member States while appearing to lack detailed fire statistics have legislation in place defining fire safety standards for bedding, mattresses and seats and these have been extensively reviewed by Sainrat [25] and by Guillaume [26].

Bearing in mind the above discussion on clothing fire hazards, **Figure 1.3** shows that the fatality rate associated with clothing has changed little over 15 year period where neither of these factors would be expected to have influence. UK annual deaths as recorded in the UK Fire Statistics [11] involving clothing (which ignore the HASS statistics which have emphasized the importance of nightwear-related fatalities [13, 14]) usually fluctuate within a 39-83 fatality range and as a group have largely been ignored by both government and the textile industry outside of the areas of nightwear [27] and protective clothing [28]. Clothing fires tend to be of an individual nature and so receive little public attention and hence legislative pressure unless common groups of hazard are identified. In fact the USA is unique in having a fundamental minimum flammability requirement which all consumer apparel textiles should conform to and defined in the standard CFR 1610 [29]

(45^{o}, 1 s ignition). This regulation falls under the US Flammable Fabrics Act 1953 which covers clothing, children's nightwear, carpet and rugs, mattresses [30].

Legislation and regulation usually occur only when large loss of life or property occurs and in both the USA and UK legislation for nightwear, in particular, has been recognised for over 50 years and other countries have since adopted similar regulations especially for nightwear worn by children as reviewed by Horrocks et al. [13]. The impact of fire-related incidents and their impact on legislation in the UK have been briefly reviewed to illustrate how the need the increasing safety levels and hence fire retardant textiles are related [31].

However, more generally in the EU, the potential safety of textiles exposed to fire hazards falls within the General Product Safety Directive (GPSD) of 2001, which is the primary instrument to protect consumer health and safety with regard to products, although it does not consider effects on the environment. If there are no specific national regulations, the safety of a product is assessed in accordance with any one of the following: relevant European standards, Community technical specifications, codes of good practice, or "the state of the art and the expectations of consumers" [32]. This does not replace already existing national regulations such as the UK 1988 furniture regulations [13] but acts as a safety net for non-regulated items. However, at the present time, no previously non-regulated textile items in the UK have been identified for special treatment. In the USA, the Consumer Product Safety Act of 1972 has a similar overarching function with regard to the fire safety of consumer textiles – this now has subsumed the earlier US Flammable Fabrics Act 1953 [30].

In many large scale fires, textiles present at each scene, have functioned as the material first ignited by the relevant igniting source as indicated in **Figure 1.1**. Secondly and subsequently, the speed with which this caused the fire to grow and spread to adjacent materials, was and continues to be a significant feature in the inability of victims to escape or the fire fighters to bring the fires under control. Therefore, these catastrophic fires serve to demonstrate more obviously the ignitability of textiles in the first place followed by the associated speed with which the resulting fire can grow. It is rarely the direct causes of the fire, such as burn severity, which are the prime causes of death, however, but the affects of the smoke and emitted fire gases which cause disorientation and impede escape initially followed by subsequent incapacitation, asphyxiation and death [11]. Only in clothing-related fires are injury and death caused primarily by burns, especially when loose fitting and worn directly over the body such as nightwear and summer dresses.

Last but not least are the fire hazards of textiles used under conditions where the hazard is particularly high and these include contract furnishing in public buildings and textiles in defence, civil emergency and first response sectors and industrial, aerospace and transport sectors where textiles are designed not only for personal protection against specific fire hazards but also comprise major structural elements including textile-reinforced composites. It is within these areas, reviewed in detail elsewhere [33-36] as well as both domestic and contract furnishing sectors where flame retardant textiles find greatest use and require also the greatest level of sophistication in that in addition to conferring the desired level of durable flame retardancy, they must also have minimal effects on the other desirable properties required of the product.

1.3 **Glossary of terms**

The whole area of textile and other material burning hazard and their related risk-reducing methodologies use a number of terms which in some cases may be quite confusing to the non-specialist within the fields of fire science and fire resistance. The following list of terms is taken from Lewin [4] and includes a number of additions and variations relating to the whole area of flame retardant fabrics and its literature:

Pyrolysis. Irreversible chemical decomposition due to non-oxidative heating.

Combustion. Self-catalyzed exothermic reaction involving fuel and oxidizer.

Flames. Combustion processes in the gas phase accompanied by emission of visible light.

Ignition. Initiation of combustion.

Autoignition. Spontaneous ignition of a material in air.

Igntion time or time to ignite. The time taken for a sample to ignite when subjected to an ignition source, a direct heat flux or both.

Flammability. Tendency of a material to burn with a flame.

To char. Carbonaceous residue that can form during pyrolysis or combustion.

Afterglow. Glowing combustion in a material after cessation (natural or induced) of flaming.

Afterglow time. The time the flame continues to burn after the ignition flame is removed.

Smouldering. Combustion without flame and without prior flaming combustion, but usually with incandescence and smoke.

Smoke. Fine dispersion in air of particles, individually invisible, of carbon and other solids and liquids resulting from incomplete combustion. Opaque due to scattering and/or absorption of visible light.

Flame propagation. Spread of flame from region to region in a combustible material (burning velocity = rate of flame propagation). In textile fabrics, the time to burn a specified length of fabric is defined.

Self-extinguishing. Incapable of sustained combustion in air under the specified test conditions after removal of external heat source.

Residual flame time. The time burning fragments (melt drip) falling from the fabric burn on the bottom of the test cabinet.

Fire resistance. Capacity of a material or structure to withstand fire without losing its functional properties.

Flame resistance. Property in a material of exhibiting resistance to ignition and/or minimal flammability; the term is often synonymous with *flame retardance* but may be considered to relate to fabrics which do not ignite under a flame but may be damaged by it.

Flame retardance or retardancy. Property in a material of exhibiting resistance to ignition and reduced flammability; the term is often synonymous with *flame resistance* but may be considered to relate to fabrics which will ignite under a flame.

Flame retardant. Chemical compound capable of imparting flame resistance to (reducing the flammability of) a material to which it is added or combined with.

Effectiveness. Ability of flame retardant to decrease flammability of the polymer substrate in which it is present.

Synergism. Observed effectiveness of combinations of compounds greater than the sum of the effects of individual components.

Antagonism. Observed effectiveness of combinations of compounds smaller than the sum of the effects of individual components.

Limiting Oxygen Index (LOI). Minimum percentage oxygen in the environment that sustains burning under specified text conditions.

Vertical, horizontal, 45° angle (strip) test. Orientation of the test specimen during flammability test under specified conditions.

Flame spread. Extent of propagation of flame in space or over specimen surface under specified test conditions.

Char length. Difference between original length and remaining unburned length of material after testing specimen by exposure to a flame.

Damaged length. The extent of damage produced over the specimen by an ignition source and subsequent the subsequent substrate ignition. It may include char, formation of a hole, discoloured region, zone having reduced tensile properties or a combination thereof.

Rate of heat release. Amount of heat released per unit time at a given time by specimen burning under specified test conditions.

Peak heat release rate. The maximum rate of heat release following the ignition of a sample.

Comonomer. Compound added in polymer synthesis and becoming a part of the polymer molecule.

Additive. Compound added after the polymer has been synthesized but before or during its conversion to final form (e.g. fibre, plastic), not covalently bound to polymer substrate.

Finish. Compound or combination of compounds added after conversion to end product (e.g. fibre, yarn, fabric). May be chemically bonded or deposited on fibre, yarn and/or fabric surfaces.

Coating. A layer of secondary material comprising a flame retardant and a binder or a flame retardant resin deposited on the fabric surface or within the fabric surface.

Back-coating. A coating applied to the reverse face of a fabric in a manner that does not affect the aesthetics or other properties of the face.

1.4 Hazard assessment and flame retardance testing methodologies

A list that more specifically focuses up on terminology relating to the testing of textiles includes the following [37] some of which will overlap with those above:

Ignition: flaming of the test specimen for a period of 1 s or more after removal of the igniting flame.

Flaming: combustion in gaseous phase with emission of light.

Glowing: combustion of a material in the solid phase without flame but emission of light from the combustion zone.

Smouldering: combustion of a material with or without emission of light generally evidenced by smoke.

Melting: liquefaction of material when exposed to heat to the extent of forming a hole in its structure, either by shrinking and/or dripping away under the specified test conditions.

Flame spread time: the time taken by a flame on a burning material to travel a specified distance measured from when the igniting flame is applied or after it has been removed.

Flaming debris: materials separating from the specimen during the test procedure and falling below the initial lower edge of the specimen and continuing to flame as they fall.

Afterglow time: the time for which a material continues to glow, under specified test conditions, after cessation of flaming or after removal of the ignition source, ignoring glowing debris.

Surface flash: rapid spread of flame over the surface of a material without ignition of its basic structure.

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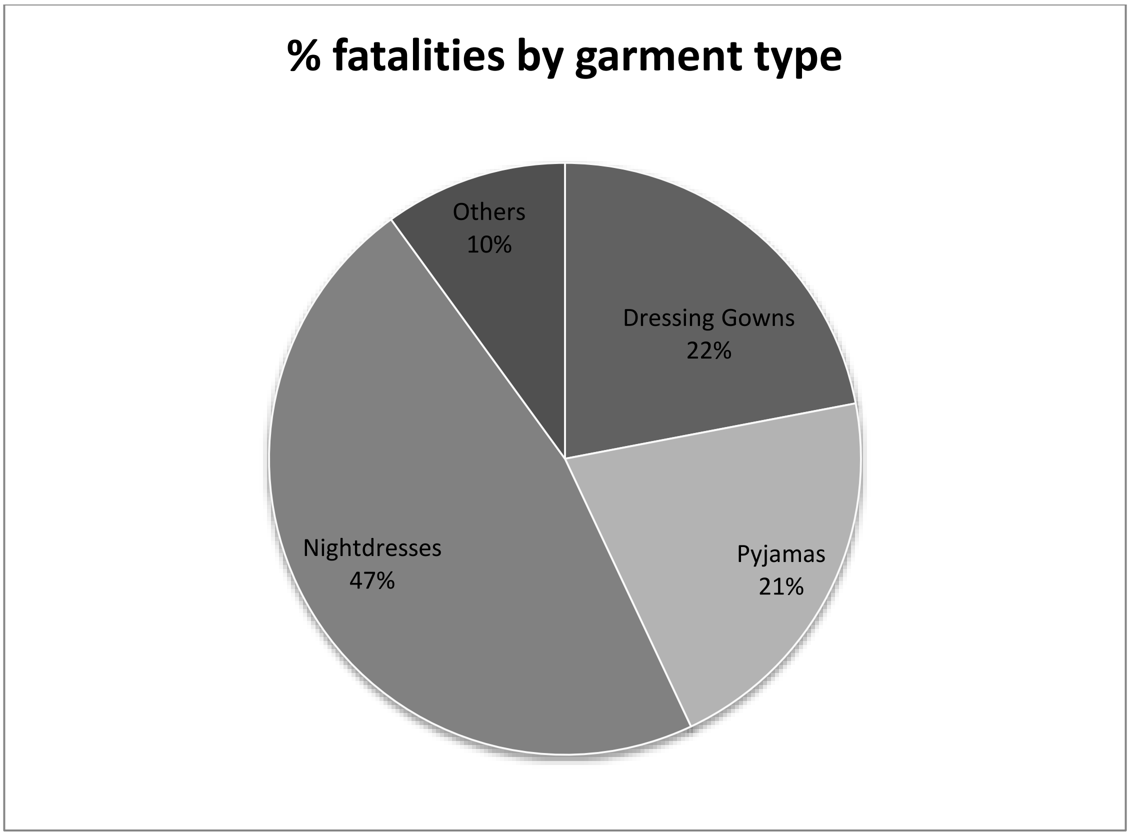

Figure 1.1. Garment types involved in nightwear clothing fire incidences (compiled from HASS data for the period 1990-1998) [13]

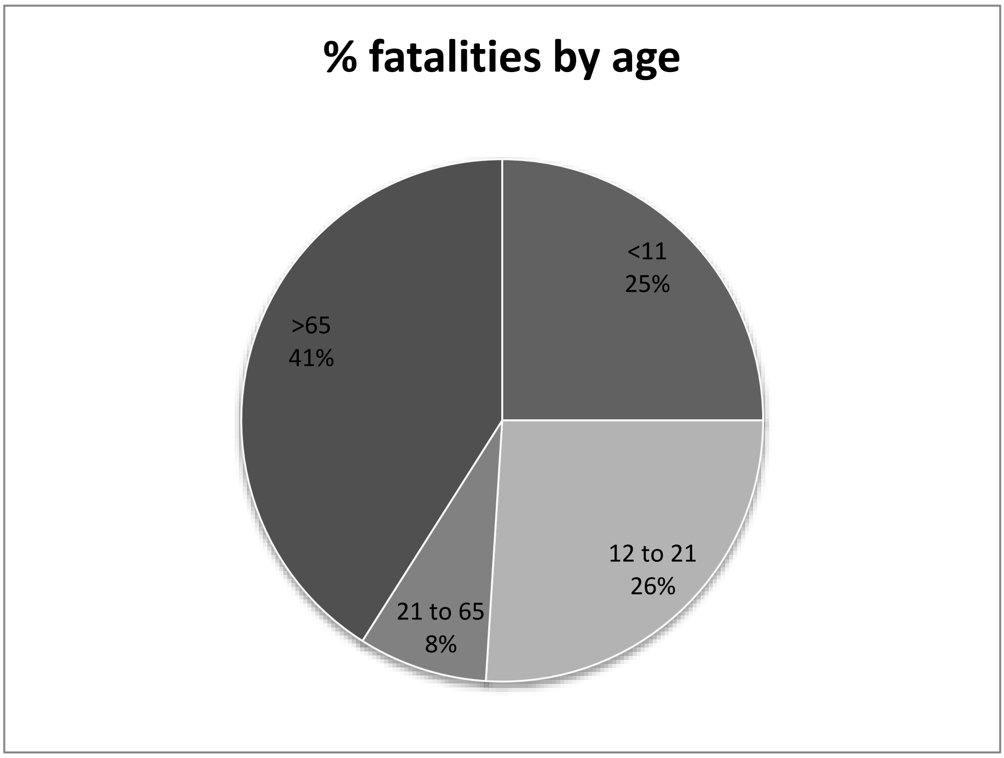

Figure 1.2. Age-wise distribution of clothing fatalities (compiled from HASS data for the period 1990-1998) [13]

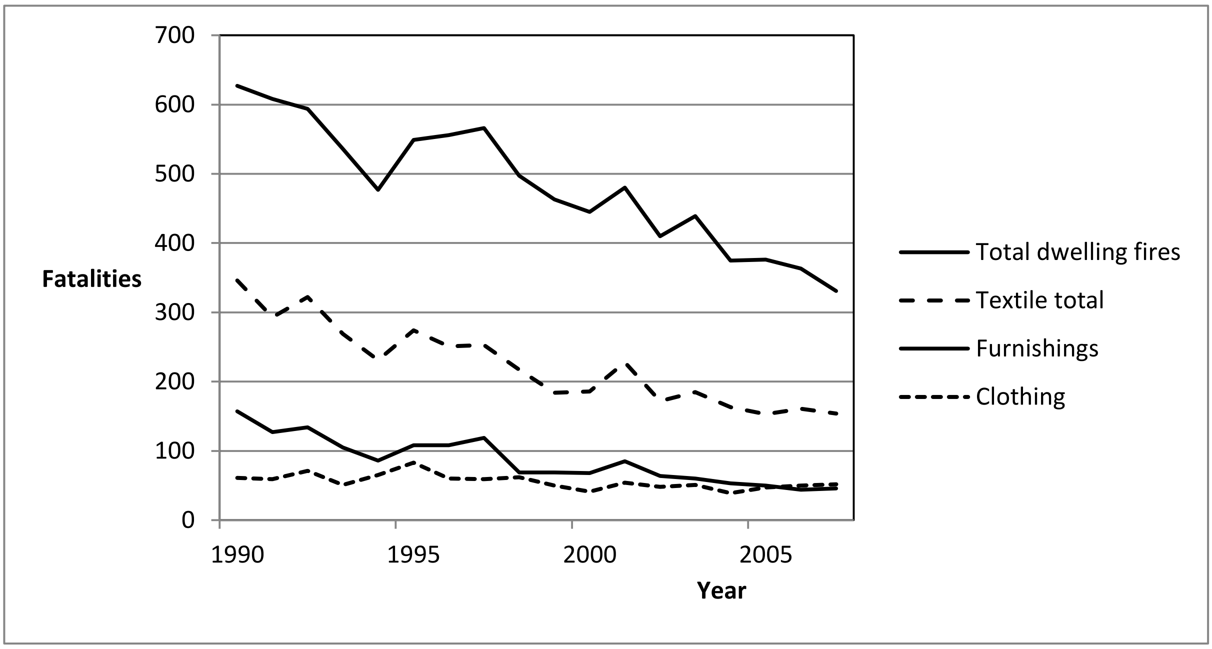

Figure 1.3. UK Fire death statistics for fatalities in dwellings from 1990-2007 [11]

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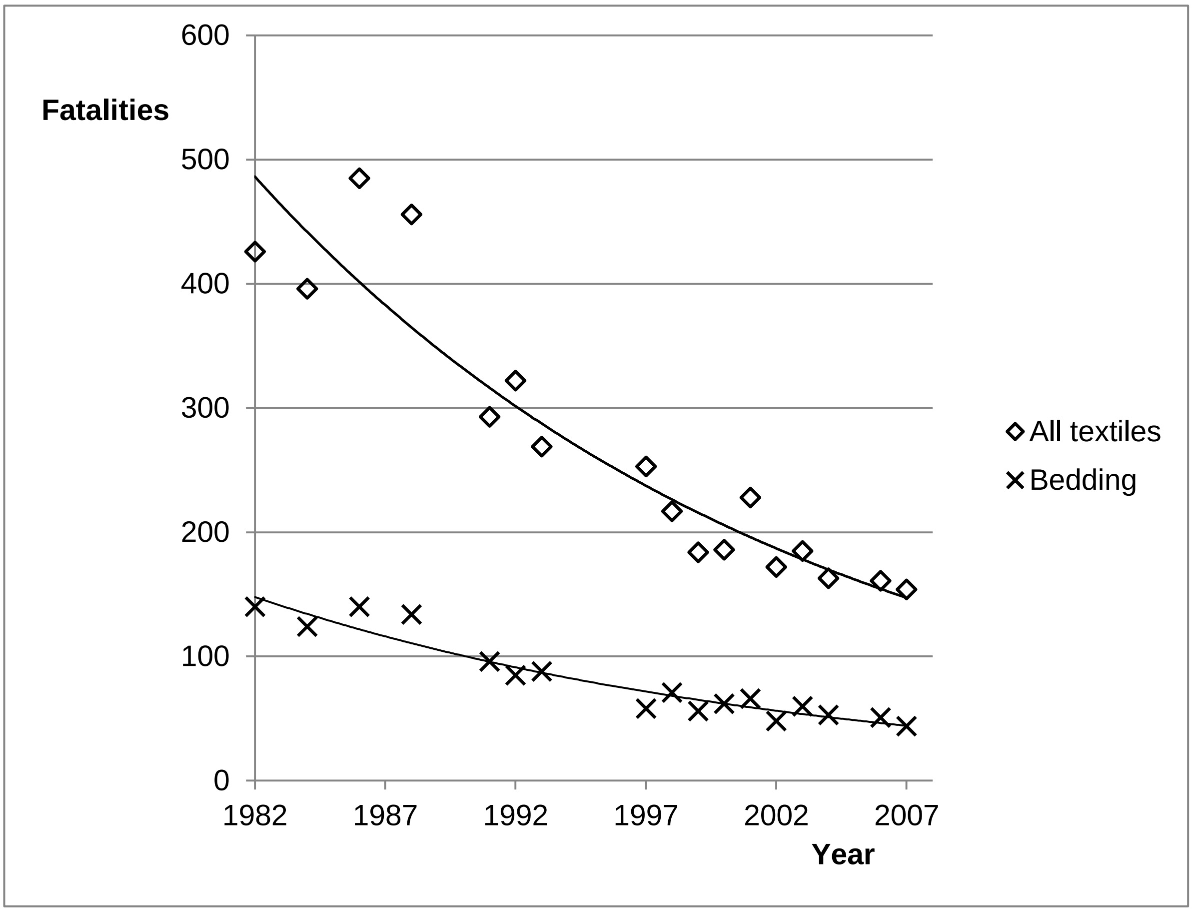

Figure 1.4. UK bedding related fatalities from 1988 to 2007 [11]